

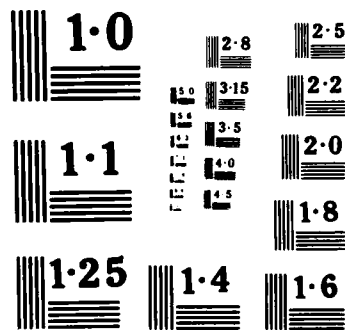
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Figure 1 displays a sequence of 100 small images arranged in a 10x10 grid. The sequence shows a white dot moving from the top-left corner towards the bottom-right corner. The first 50 images (left half) show the dot moving from the top-left towards the center, and the second 50 images (right half) show the dot moving from the center towards the bottom-right. The dot is a small white square on a black background.



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THESIS

CODE DIVISION MULTIPLE ACCESS
APPLIED TO FIBER OPTIC DATA TRANSMISSION

by

Tracey Alan Fischer

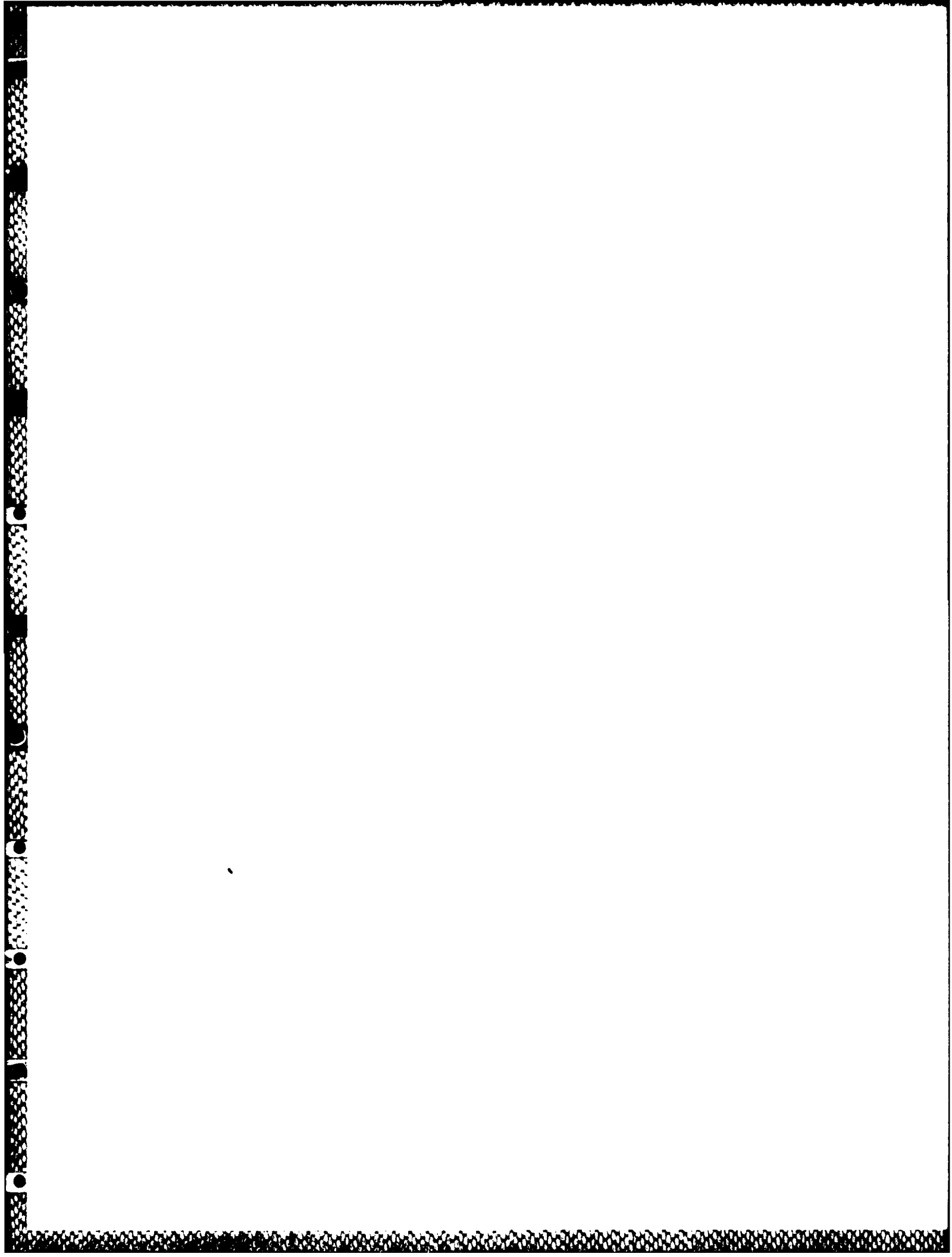
September 1987

Thesis Advisor: John P. Powers

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REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION Unclassified			1b RESTRICTIVE MARKINGS		
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for Public release; distribution is unlimited		
2b DECLASSIFICATION/DOWNGRADING SCHEDULE			5 MONITORING ORGANIZATION REPORT NUMBER(S)		
4 PERFORMING ORGANIZATION REPORT NUMBER(S)			7a NAME OF MONITORING ORGANIZATION Naval Postgraduate School		
6a NAME OF PERFORMING ORGANIZATION Naval Postgraduate School		6b OFFICE SYMBOL (if applicable) 62		7b ADDRESS (City, State, and ZIP Code) Monterey, California 93943-5000	
8a NAME OF FUNDING/SPONSORING ORGANIZATION		8b OFFICE SYMBOL (if applicable)		9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c ADDRESS (City, State, and ZIP Code)		10 SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO		PROJECT NO	TASK NO
					WORK UNIT ACCESSION NO
11 TITLE (Include Security Classification) CODE DIVISION MULTIPLE ACCESS APPLIED TO FIBER OPTIC DATA TRANSMISSION					
12 PERSONAL AUTHOR(S) Fischer, Tracey A.					
13a TYPE OF REPORT Master's Thesis		13b TIME COVERED FROM _____ TO _____		14 DATE OF REPORT (Year, Month, Day) September 1987	
15 PAGE COUNT 63					
16 SUPPLEMENTARY NOTES					
17 COSAT CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB GROUP	Code Division Multiple Access		
			Optical Data Link		
19 ABSTRACT (Continue on reverse if necessary and identify by block number) The potential for applying Code Division Multiple Access techniques to achieve simultaneous multichannel data transmission over a fiber optic data link is investigated. Initially, a slow speed data link at 1 kilobits per second is examined to verify the ability to perform data correlation on a two stream system. Finally, a design for a high speed link operation at 166.7 kilobits per second is proposed.					
20 DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a NAME OF RESPONSIBLE INDIVIDUAL J.P. Powers			22b TELEPHONE (Include Area Code) 408-649-8349		22c OFFICE SYMBOL 62



Approved for Public Release; Distribution Unlimited

Code Division Multiple Access
Applied to Fiber Optic Data Transmission

by

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Lieutenant, United States Navy
B.S., United States Naval Academy, 1980

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1987


Author:



Tracey Alan Fischer

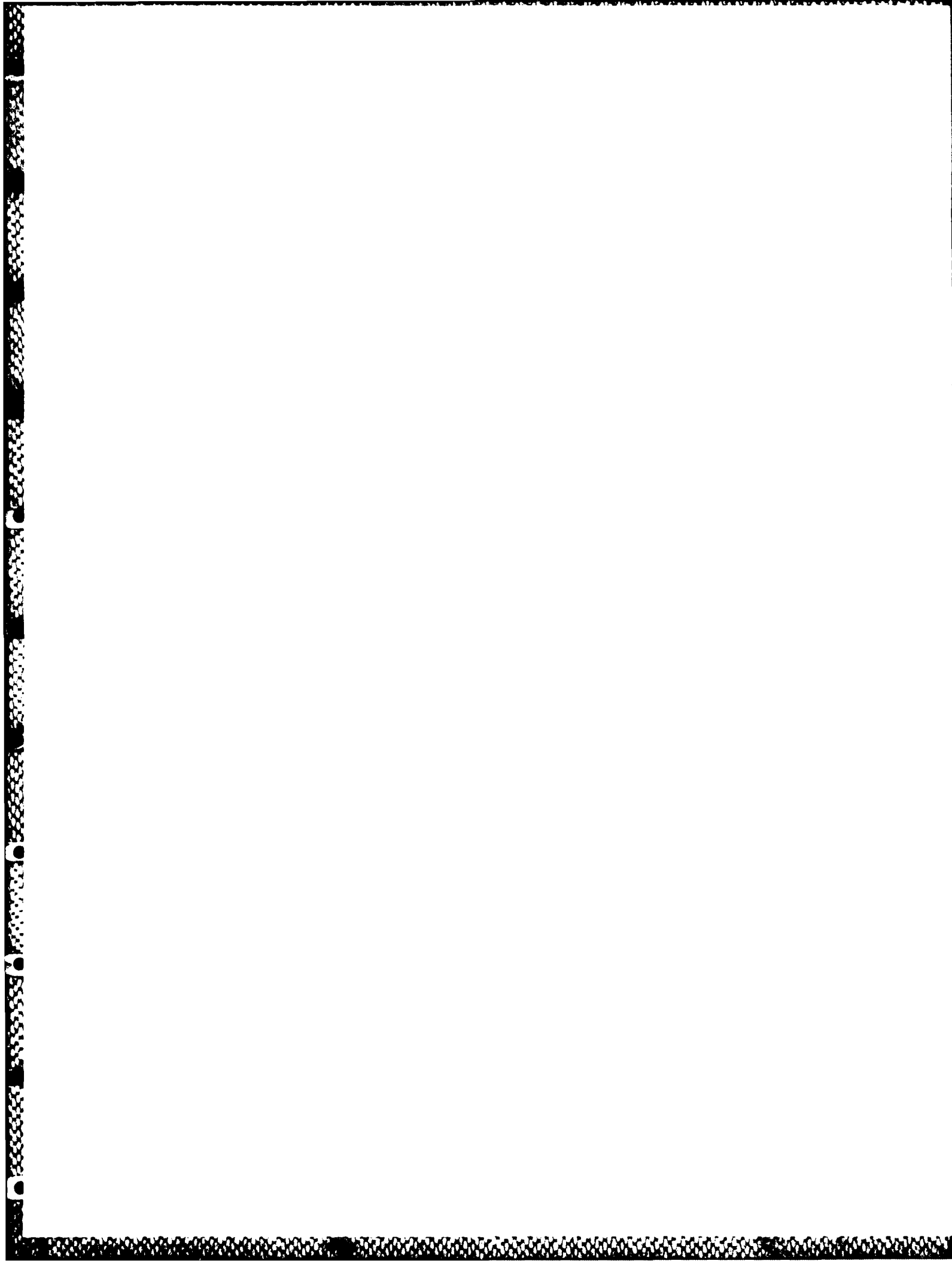
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ABSTRACT

The potential for applying Code Division Multiple Access techniques to achieve simultaneous multichannel data transmission over a fiber optic data link is investigated. Initially, a slow speed data link at 1 kilobits per second is examined to verify the ability to perform data correlation on a two data stream system. Finally, a design for a high speed link operating at 166.7 kilobits per second is proposed.



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I. INTRODUCTION

Gathering information from the acoustic signals present in the oceans is a task that draws much attention from the communities who work in and around the oceans. The capability to monitor acoustic properties of the ocean with sensors and then to efficiently transmit the data ashore becomes the center of focus when it is desired to maintain continuous real time capability. Specifically, the ability to simultaneously transmit the data ashore over a single channel without the need to delay the information in time or to limit the portion of the frequency spectrum they occupy becomes a major objective when considering a system for this purpose.

The systems studied in this thesis are based on being used as the transmission medium for an ocean-deployed acoustic sensor array with shore-based signal processing. Primary emphasis, however, is on implementation of a suitable Code Division Multiple Access (CDMA) system to satisfy the operation requirements of an ocean sensor array.

This thesis investigates the possible application of CDMA techniques as a method of transmitting several data streams over a common optical cable simultaneously. The initial investigation provides a follow-on design and test of a fiber optic digital data link to a previously built system. The

data link provides transmission of Manchester encoded data at a rate of 3.0 Megabits per second (Mbps). This design provided the ground work for using the fiber optic data link with a Manchester encoded data stream, thereby validating the ability to transmit and recover data without introducing additional errors into the process.

The major thrust of the remaining research and design was in the area of CDMA. Initial data link implementation is of a 2 channel system capable of handling digital data at 1 kilobit per second (Kbps). This portion of research provided the verification of the ability to transmit simultaneous data streams over the same channel and then to recover each without significant introduction of errors.

The last portion of research is the preliminary design of a high speed data link capable of handling Manchester encoded data at a rate of 166.7 Kbps. The intent of this research is to provide recommendations and direction for future research in the area of CDMA techniques when implemented over a optical channel. A specific working prototype is not intended to result from this work.

II. SYSTEM REQUIREMENTS

A. BACKGROUND

The desired underwater acoustic array needs to have multiple sensors all accessing a common fiber optic cable for data transmission to a shore site for signal processing. Each of the sensors will provide the digital signal to the data link portion of the array where all sensor data streams will be added together. At the receiver each of the data streams is to be separated for individual signal processing. The data link is to have the capability of transmitting the data along an optical fiber for several kilometers (km) through an ocean environment. The system must also have the high reliability and long lifetime typical for military application. It is desired that the system have a frequency coverage of DC to 20 kilohertz (KHz). Figure 2.1 provides a simple block diagram of the system.

B. PREVIOUSLY CONSIDERED SYSTEMS

Two options that have been previously considered for implementing the desired system are time division multiplexing (TDM) and frequency division multiplexing (FDM). Reference 1 looked at TDM in the design and construction of a microprocessor controlled system. In this system analog

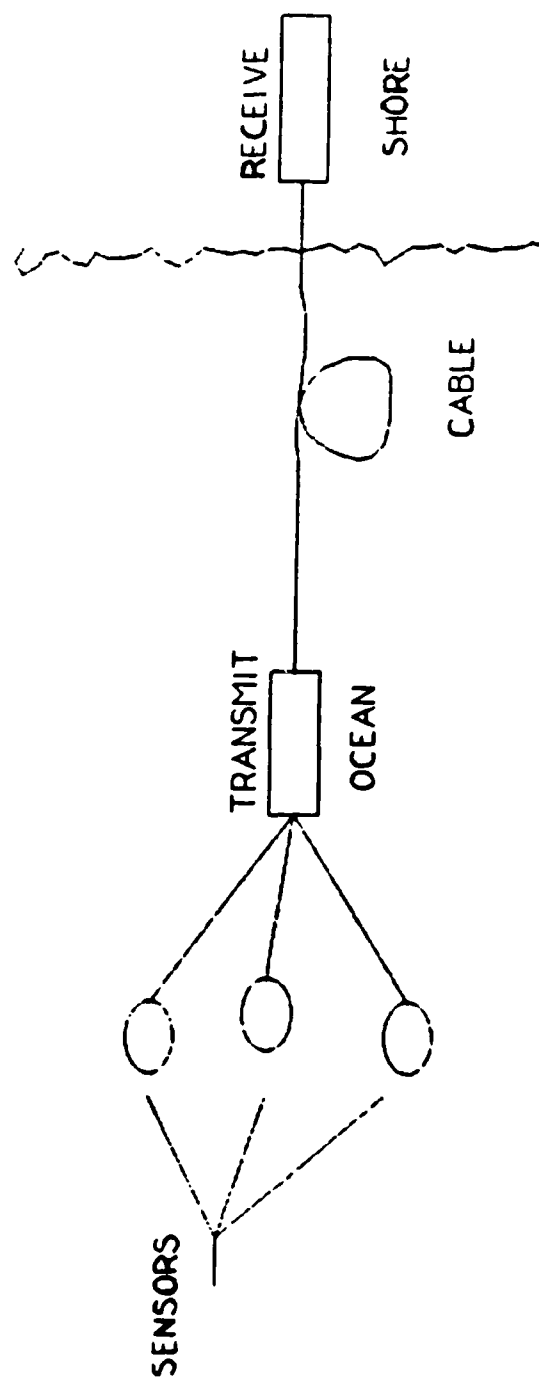


Figure 2.1 System Block Diagram

signals are sampled and converted into digital information, which are multiplexed together and converted into a single Manchester encoded digital word for transmission to the shore receiver. The sensors' frequency response is DC to 20 KHz and the data transmission rate is 3 Mbps. The system's microprocessor provides addressability for up to four individual sensor's outputs for multiplexing, and later, separation for processing [Ref. 1]. Figure 2.2 shows a block diagram of the TDM system.

As an addition to the TDM system in reference 1, a fiber optic data link was constructed, for this thesis study, using Hewlett Packard's HBFR-0400 Low Cost Miniature Fiber Optic Components. Reference 2 provided a simple design of a 5 Mbps data link. This link is shown in Figure 2.3. For maximum transmission length, a forward drive current of 40 milliamperes (mA) was selected. This provides for a theoretical fiber cable length of 2.2 km, while ensuring that the transmitter is not overdriven (60 mA). This selection is based on Figure 2.4 from reference 2 which shows link length as a function of drive current under various operating conditions. From Table 2.1, the recommended operating conditions for the HBFR-1402 Fiber Optic Transmitter and the HBFR-2402 Fiber Optic Receiver are obtained. The transmitter driver circuit is designed to ensure that the drive current is

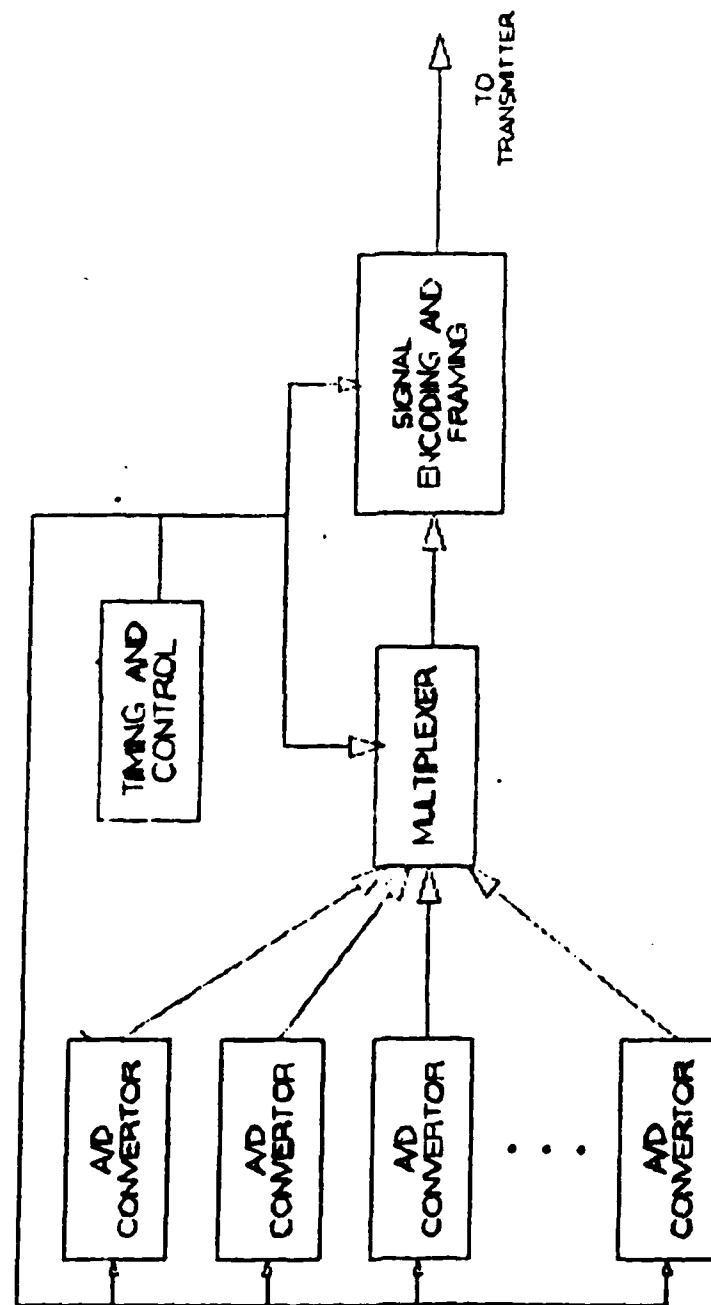


Figure 2.2 TDM Block Diagram [Ref. 1]

NOTE
IT IS ESSENTIAL THAT A BYPASS CAPACITOR (0.01 μ F TO 0.1 μ F CERAMIC) BE CONNECTED FROM PIN 2 TO PIN 7 OF THE RECEIVER. TOTAL LEAD LENGTH BETWEEN BOTH ENDS OF THE CAPACITOR AND THE PINS SHOULD NOT EXCEED 20 mm.

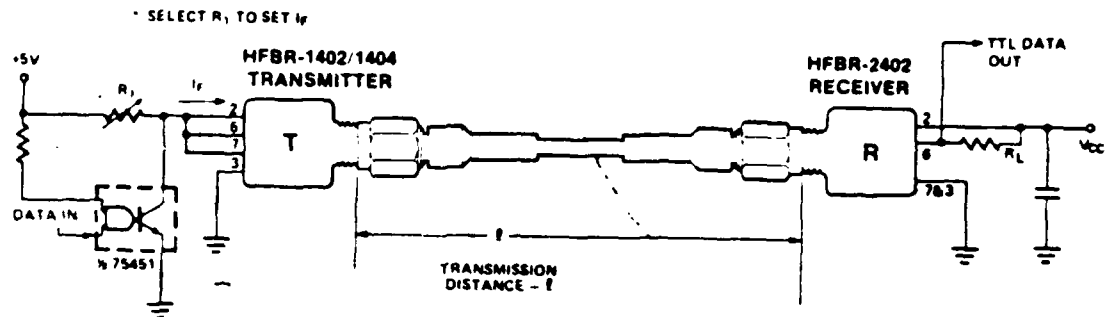


Figure 2.3 Fiber optic Data Link [Ref. 2]

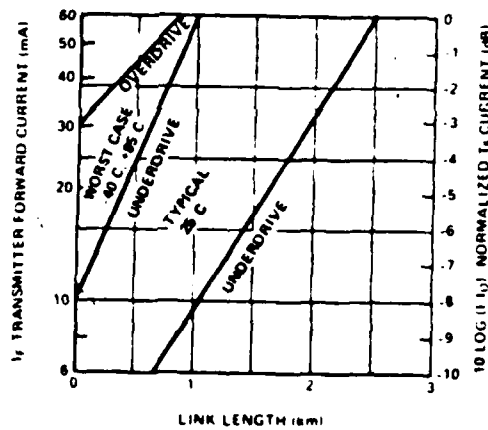


Figure 2. HFBR-1402/HFBR-2402 Link Design Limits
with 100/140 μ m Cable (HFBR-3000 Series)

Figure 2.4 Length versus Drive Current [Ref. 2]

TABLE 2.1 OPTICAL TRANSMITTER AND RECEIVER OPERATING CHARACTERISTICS [Ref. 2]

Electrical/Optical Characteristics

Parameter	Symbol	Min.	Max.	Units		
TRANSMITTER						
Ambient Temperature	T _A	-40	-85	°C		
Peak Forward Input Current	I _{F PK}		60	mA		
DC Forward Input Current	I _{FDC}		60	mA		
Parameter	Symbol	Min.	Typ. [2]	Max.	Units	Conditions
Forward Voltage	V _F	1.58	1.80	2.19	V	I _F = 60 mA
Forward Voltage Temperature Coefficient	V _F /T		0.86		mV/°C	I _F = 60 mA
Reverse Input Voltage	V _{BR}	1.8	3.8		V	I _R = 100 μA
Peak Emission Wavelength	λ _P		820		nm	
Diode Capacitance	C _T		145		pF	V = 0, f = 1 MHz
Optical Power	ΔP _T /ΔT		-0.016		dB/°C	I _F = 60 mA
Thermal Resistance	θ _{JA}		240		°C/W	
Numerical Aperture (HFBR-1402)	NA ₁₄₀₂		49			
Numerical Aperture (HFBR-1404)	NA ₁₄₀₄		31			
Optical Port Diameter (HFBR-1402)	D _{T1402}		290		μm	
Optical Port Diameter (HFBR-1404)	D _{T1404}		150		μm	

RECEIVER						
Ambient Temperature	T _A	-40	-85	°C		
Supply Voltage	V _{CC}		5.25	V		
Fan Out TTL	Note 1, Fig. 1	N	5			
Parameter	Symbol	Min.	Typ. [2]	Max.	Units	Conditions
High Level Output Current	I _{OH}		5	250	μA	V _O = 1.8V P _R = -40 dBm
Low Level Output Voltage	V _{OL}		0.4	0.5	V	I _O = 8 mA P _R = -24 dBm
High Level Supply Current	I _{CCH}		3.5	6.3	mA	V _{CC} = 5.25 V P _R = -40 dBm
Low Level Supply Current	I _{CCL}		6.2	10	mA	V _{CC} = 5.25 V P _R = -24 dBm
Equivalent N.A.	NA		50			
Optical Port Diameter	D _R		400		μm	

Notes:

1. 8 mA load. 5 x 16 mA. $R_L = 560 \Omega$

set at 40 mA. The value of R_1 is found from equation 1:

$$R_1 = (V_{CC} - V_f) / I_f \quad [1]$$

where V_{CC} is 5 volts, I_f is 40 mA, and V_f is 1.85 volt as determined from Figure 2.5 for a I_f of 40 mA. R_1 was calculated to be 78.75 ohms. A 82 ohm resistor was used, thus the actual drive current is slightly less and this reduces the link length in turn. Through iteration I_f is found to be 39 mA, V_f is 1.8 volts, and link length is 2.1 km. From reference 2, the load resistor at the output of the receiver is selected at 560 ohms; this selection is based on fan out as shown in note 1 of Table 2.1. For this configuration the theoretical bit error rate was less than 10^{-9} . To interface the TDM system with the fiber optic data link, the data out of the RS-232 was applied to the dual peripheral driver (75451) on the data link. The output of the optical receiver was then returned to the TDM system through the RS-232 port. Comparison of reconstructed signals from the TDM system with and without the data link in place showed no degradation in performance. The distance that this link functions over can be increased by selecting different fiber optic components and by using repeaters.

Reference 3 demonstrated the application of FDM techniques as a possible system capable of meeting the requirements of the transmission media for the underwater

acoustic sensor array. The system provides the ability to multiplex four audio channels, whose frequency response is DC to 16 KHz, transmit the signal over a common optical fiber, and then recover the channels individually after transmission over a length of fiber 1 km long [Ref. 3]. Figure 2.6 is a block diagram of the FDM system.

An alternative multiplexing scheme is code division multiplexing. We now consider a description of this technique as implemented through CDMA.

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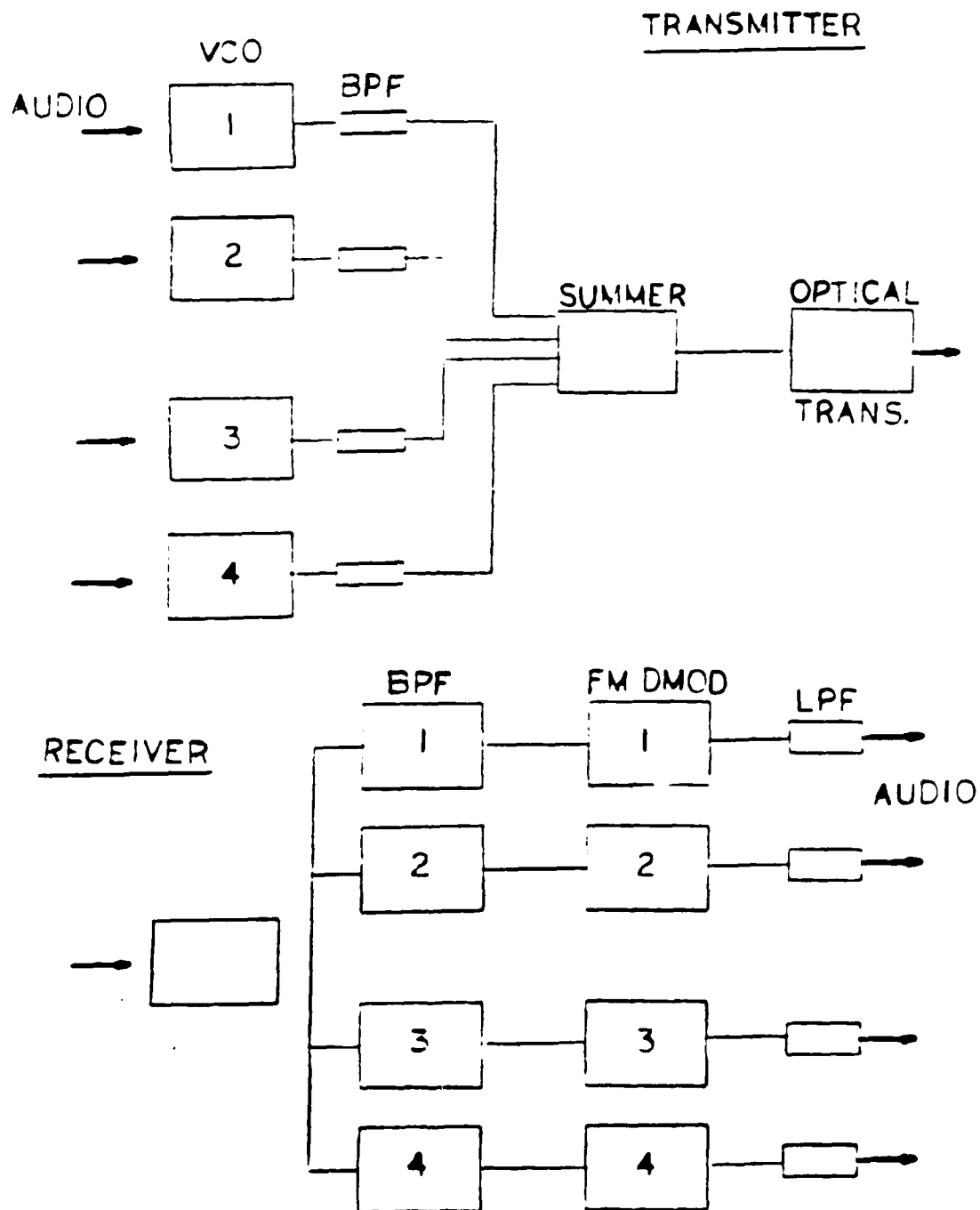


Figure 1. System Block Diagram

Figure 2.6 FDM Block Diagram [Ref. 3]

III. THEORY OF CODE DIVISION MULTIPLE ACCESS

A. THEORY

The desirability of transmitting several data streams on the same channel simultaneously while maintaining the ability to recover the data without a significant decrease in system performance is one of the foremost problems in communications. TDM and FDM techniques have long been used to circumvent the problem by segregating the data streams in either time or frequency. However, both TDM and FDM have their own specific limitations and drawbacks. Another technique that can be used to allow simultaneous use of a channel by several data streams without all the limits of FDM or TDM is CDMA.

In CDMA carefully selected digital sequences are used to form codewords. The two most popular digital sequence types used are Gold codes and Kasami codes [Ref. 4]. The codewords modulate the data streams such that the codewords effectively become identifiers for different receivers capable of discriminating against the unwanted data streams. Data rate and binary sequence (codeword) are related in length. This relationship is:

$$R = r \times L \quad [2]$$

where R is codeword rate, r is data rate, and L is codeword

length (in bits). Equation 2 shows that for high data rates, extremely high codeword rates result. The higher data rates capable of on optical fiber links, however, make the use of them natural candidates for this method of multiplexing.

Data modulation is a modulo 2 multiplication process. This is achieved by passing the data and code through a logical exclusive nor (XNOR) gate. The resultant digital signal is then either the code or its complement. The signal is now ready to be transmitted.

The receiver uses the same code generated in the transmitter to recover the data. Data recovery is achieved by a correlation process. Synchronization between transmitter's code rate and the receiver's code rate is done by either a Tau-Dither loop or an early-late gate correlator [Ref. 4]. After correlation, the signal is filtered to recover the original data. Figure 3.1 shows a typical CDMA system.

The number of data streams that can be simultaneously transmitted and received is limited by two factors. First, each data stream must have a unique code for modulation. Essentially, each of the codes used to modulate the data will identify that data stream as being a unique and separate entity. The code must provide enough orthogonal separation so as not to be confused with other codes. Second, each of the codes must have a sufficient crosscorrelation to autocorrelation ratio to ensure that false correlation does not occur. Again, the crosscorrelation to autocorrelation

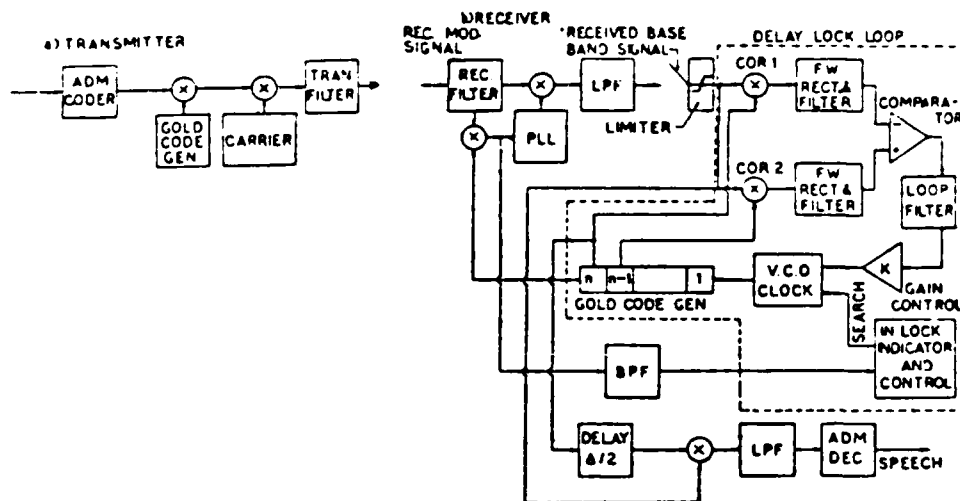


Figure 3.1 Typical CDMA System [Ref. 8]

ratio results from the orthogonality relationship between the selected codes. The closer to exact orthogonality that exists between the codes, the greater the difference in autocorrelation to crosscorrelation. Obviously, the factor that limits the number of data streams that can access the same channel simultaneously is then solely a function of the code used.

The most popular types of codes used are all composite codes. Composite codes are formed by combining maximal linear sequences. Composite codes have special properties that make them advantageous for use in special circumstances, as is the case of simultaneous data transmission. Maximal linear sequences are formed by delay elements and linear combinations in a feedback path, known as a feedback shift register (FSR), such that the number of delay elements determines a maximum number of states that can exist. The number of states in the sequence is:

$$L = 2^n - 1 \quad [3]$$

where L is the number of states that exist in the sequence before it repeats itself and n is the number of delay elements. Many possible linear combinations of the delay element exist, yet not all may result in a maximal linear sequence [Ref. 5]. Table 3.1 shows the number of maximal linear sequences available from various numbers of delay elements and their associated linear combinations.

TABLE 3.1 FEEDBACK CONNECTIONS FOR MAXIMAL LENGTH LINEAR SEQUENCES [Ref. 5]

Table 3.7 Feedback Connections for Linear m -Sequences

Number of Stages	Code Length	Maximal Taps
2	3	[2, 1]
3	7	[3, 1]
4	15	[4, 1]
5	31	[5, 2][5, 4, 3, 2][5, 4, 2, 1]
6	63	[6, 1][6, 5, 2, 1][6, 5, 3, 2]
7	127	[7, 1][7, 3][7, 3, 2, 1][7, 4, 3, 2] [7, 6, 4, 2][7, 6, 3, 1][7, 6, 5, 2] [7, 6, 5, 4, 2, 1][7, 5, 4, 3, 2, 1]
8	255	[8, 4, 3, 2][8, 6, 5, 3][8, 6, 5, 2] [8, 5, 3, 1][8, 6, 5, 1][8, 7, 6, 1] [8, 7, 6, 5, 2, 1][8, 6, 4, 3, 2, 1]
9	511	[9, 4][9, 6, 4, 3][9, 8, 5, 4][9, 8, 4, 1] [9, 5, 3, 2][9, 8, 6, 5][9, 8, 7, 2] [9, 6, 5, 4, 2, 1][9, 7, 6, 4, 3, 1] [9, 8, 7, 6, 5, 3]
10	1023	[10, 3][10, 8, 3, 2][10, 4, 3, 1][10, 8, 5, 1] [10, 8, 5, 4][10, 9, 4, 1][10, 8, 4, 3] [10, 5, 3, 2][10, 5, 2, 1][10, 9, 4, 2]
11	2047	[11, 1][11, 8, 5, 2][11, 7, 3, 2][11, 5, 3, 5] [11, 10, 3, 2][11, 6, 5, 1][11, 5, 3, 1] [11, 9, 4, 1][11, 8, 6, 2][11, 9, 8, 3]
12	4095	[12, 6, 4, 1][12, 9, 3, 2][12, 11, 10, 5, 2, 1] [12, 11, 6, 4, 2, 1][12, 11, 9, 7, 6, 5] [12, 11, 9, 5, 3, 1][12, 11, 9, 8, 7, 4] [12, 11, 9, 7, 6, 5][12, 9, 8, 3, 2, 1] [12, 10, 9, 8, 6, 2]
13	8191	[13, 4, 3, 1][13, 10, 9, 7, 5, 4] [13, 11, 8, 7, 4, 1][13, 12, 8, 7, 6, 5] [13, 9, 8, 7, 5, 1][13, 12, 6, 5, 4, 3] [13, 12, 11, 9, 5, 3][13, 12, 11, 5, 2, 1] [13, 12, 9, 8, 4, 2][13, 8, 7, 4, 3, 2]
14	16,383	[14, 12, 2, 1][14, 13, 4, 2][14, 13, 11, 9] [14, 10, 6, 1][14, 11, 6, 1][14, 12, 11, 1] [14, 6, 4, 2][14, 11, 9, 6, 5, 2] [14, 13, 6, 5, 3, 1][14, 13, 12, 8, 4, 1] [14, 8, 7, 6, 4, 2][14, 10, 6, 5, 4, 1] [14, 13, 12, 7, 6, 3][14, 13, 11, 10, 8, 3]
15	32,767	[15, 13, 10, 9][15, 13, 10, 1][15, 14, 9, 2] [15, 1][15, 9, 4, 1][15, 12, 3, 1][15, 10, 5, 4] [15, 10, 5, 4, 3, 2][15, 11, 7, 6, 2, 1] [15, 7, 6, 3, 2, 1][15, 10, 9, 8, 5, 3] [15, 12, 5, 4, 3, 2][15, 10, 9, 7, 5, 3] [15, 13, 12, 10][15, 13, 10, 2][15, 12, 9, 1] [15, 14, 12, 2][15, 13, 9, 6][15, 7, 4, 1] [15, 4][15, 13, 7, 4]

TABLE 3.1 CONTINUED

Table 3.7 (Continued)

Number of Stages	Code Length	Maximal Laps
16	65, 535	[16, 12, 3, 1][16, 12, 9, 6][16, 9, 4, 3] [16, 12, 7, 2][16, 10, 7, 6][16, 15, 7, 2] [16, 9, 5, 2][16, 13, 9, 6][16, 15, 4, 2] [16, 15, 9, 4]
17	131, 071	[17, 3][17, 3, 2, 1][17, 7, 4, 3] [17, 16, 3, 1][17, 12, 6, 3, 2, 1] [17, 8, 7, 6, 4, 3][17, 11, 8, 6, 4, 2] [17, 9, 8, 6, 4, 1][17, 16, 14, 10, 3, 2] [17, 12, 11, 8, 5, 2]
18	262, 143	[18, 7][18, 10, 7, 5][18, 13, 11, 9, 8, 7, 6, 3] [18, 17, 16, 15, 10, 9, 8, 7] [18, 15, 12, 11, 9, 8, 7, 6]
19	524, 287	[19, 5, 2, 1][19, 13, 8, 5, 4, 3] [19, 12, 10, 9, 7, 3][19, 17, 15, 14, 13, 12, 6, 1] [19, 17, 15, 14, 13, 9, 8, 4, 2, 1] [19, 16, 13, 11, 19, 9, 4, 1][19, 9, 8, 7, 6, 3] [19, 16, 15, 13, 12, 9, 5, 4, 2, 1] [19, 18, 15, 14, 11, 10, 8, 5, 3, 2] [19, 18, 17, 16, 12, 7, 6, 5, 3, 1]
20	1, 048, 575	[20, 3][20, 9, 5, 3][20, 19, 4, 3] [20, 11, 8, 6, 3, 2][20, 17, 14, 10, 7, 4, 3, 2]
21	2, 097, 151	[21, 2][21, 14, 7, 2][21, 13, 5, 2] [21, 14, 7, 6, 3, 2][21, 8, 7, 4, 3, 2] [21, 10, 6, 4, 3, 2][21, 15, 10, 9, 5, 4, 3, 2] [21, 14, 12, 7, 6, 4, 3, 2][21, 20, 19, 18, 5, 4, 3, 2]
22	4, 194, 303	[22, 1][22, 9, 5, 1][22, 20, 18, 16, 6, 4, 2, 1] [22, 19, 16, 13, 10, 7, 4, 1][22, 17, 9, 7, 2, 1] [22, 17, 13, 12, 8, 7, 2, 1][22, 14, 13, 12, 7, 3, 2, 1]
23	8, 388, 607	[23, 5][23, 17, 11, 5][23, 5, 4, 1] [23, 12, 5, 4][23, 21, 7, 5][23, 16, 13, 6, 5, 3] [23, 11, 10, 7, 6, 5][23, 15, 10, 9, 7, 5, 4, 3] [23, 17, 11, 9, 8, 5, 4, 1][23, 18, 16, 13, 11, 8, 5, 2]
24	16, 777, 215	[24, 7, 2][24, 4, 3, 1] [24, 22, 20, 18, 16, 14, 11, 9, 8, 7, 5, 4] [24, 21, 19, 18, 17, 16, 15, 14, 13, 10, 9, 5, 4, 1]
25	33, 554, 431	[25, 3][25, 3, 2, 1][25, 20, 5, 3][25, 12, 5, 4] [25, 17, 10, 3, 2, 1][25, 23, 21, 19, 9, 7, 5, 3] [25, 18, 12, 11, 6, 5, 4][25, 20, 16, 11, 5, 3, 2, 1] [25, 12, 11, 8, 7, 6, 4, 3]
26	67, 108, 863	[26, 6, 2, 1][26, 22, 21, 16, 12, 11, 10, 8, 5, 4, 3, 1]
27	134, 217, 727	[27, 5, 2, 1][27, 18, 11, 10, 9, 5, 4, 3]
28	268, 435, 455	[28, 3][28, 13, 11, 9, 5, 3][28, 22, 11, 10, 4, 3] [28, 24, 20, 16, 12, 8, 4, 3, 2, 1]

TABLE 3.1 CONTINUED

Table 3.7 (Continued)

Number of Stages	Code Length	Maximal Taps
29	536, 870, 911	[29, 2][29, 20, 11, 2][29, 13, 7, 2] [29, 21, 5, 2][29, 26, 5, 2][29, 19, 16, 6, 3, 2] [29, 18, 14, 6, 3, 2]
30	1, 073, 74, 1, 823	[30, 23, 2, 1][30, 6, 4, 1] [30, 24, 20, 16, 14, 13, 11, 7, 2, 1]
31	2, 147, 483, 647	[31, 29, 21, 17][31, 28, 19, 15][31, 3] [31, 3, 2, 1][31, 13, 8, 3][31, 21, 12, 3, 2, 1] [31, 20, 18, 7, 5, 3][31, 30, 29, 25][31, 28, 24, 10] [31, 20, 15, 5, 4, 3][31, 16, 8, 4, 3, 2]
32	4, 294, 967, 295	[32, 22, 2, 1][32, 7, 5, 3, 2, 1] [32, 28, 19, 18, 16, 14, 11, 10, 9, 6, 5, 1]
33	8, 589, 934, 591	[33, 13][33, 22, 13, 11][33, 26, 14, 10] [33, 6, 4, 1][33, 22, 16, 13, 11, 8]
61	2, 305, 843, 009, 213, 693, 951	[61, 5, 2, 1]
89 ^a	618, 970, 019, 642, 690, 137, 449, 562, 112	[89, 6, 5, 3]

Gold codes are generated by adding certain members of a family of maximal linear sequences together. The two selected base sequences are modulo 2 added bit by bit to form a completely new and unique code. From a property inherent to maximal linear sequences (the shift and add property), it is known that any phase shift between the sequences, when added, will form a new unique phase-shifted sequence of equal length to each of the base sequences. Gold showed that any two maximal linear base sequences could generate 2^{n-1} unique sequences of length 2^n-1 . [Ref. 4]

Besides being able to generate a large number of unique codes, Gold codes are also capable of being selected so that their cross-correlation is uniform and bounded. Gold developed a method of selecting maximal linear sequences as the base codes, such that their crosscorrelation and autocorrelation side lobes are bounded by equation 4,

$$R(t) \leq \begin{cases} 2^{(n+1)/2} + 1 & n \text{ is odd} \\ 2^{(n+1)/2} - 1 & n \text{ is even} \end{cases} \quad [4]$$

where $R(t)$ is the correlation function and n is number of delays [Ref. 4]. Additionally, Anderson showed an equivalent expression for the bounds on crosscorrelation for Gold codes

as a function of code length [Ref. 5]. The bounds are,

$$R(t) \leq \left(\frac{\sqrt{2} \sqrt{(1+1/L)}}{\sqrt{L}} + 1/\sqrt{2} \right)^{1/2} \quad [5]$$

where L is code length. Equation 5 shows that as L becomes large the expression converges to $\sqrt{2/L}$. When compared to Anderson's form for the crosscorrelation of maximal linear sequences,

$$R(t) \leq \frac{(1+1/L - 1/L^2)^{1/2}}{L^{1/2}} \quad [6]$$

which converge to $\sqrt{1/L}$ as L becomes large, it is seen that the crosscorrelation of Gold codes is only twice that of the crosscorrelation of a maximal linear sequence [Ref. 5]. This ensures the capability to provide sufficient margin between the autocorrelation peak and the crosscorrelation peaks for avoiding acquisition of the wrong peak during synchronization of the receiver's clock with the transmitter's clock. References 5 and 6 give algorithms for developing suitable maximal length sequences as the basis for generating the desired length Gold codes.

Data modulation by the Gold codes is a modulo 2 multiplication process, which is implemented by a XOR process.

This is achieved by using two XOR gates, with the output of the first gate providing one input to the second gate while the other input is tied high. The resulting digital signal is then the original binary sequence for a data bit "1" and the complement of the binary sequence for a data bit "0". This is illustrated in Figure 3.2. The increase in number of bits that represent each data bit is really an increase in channel bandwidth and this results in processing gain. Processing gain then is,

$$\text{Gain} = B/W \quad [6]$$

where B is bandwidth of the code and W is the bandwidth of the data. Processing gain in a CDMA system refers to the reduction of the effects of an interfering signal on the reception of the desired signal [Ref. 7]. It therefore follows that processing gain is a measure of the system's ability to handle additional signals simultaneously without interference occurring [Ref. 8].

The CDMA receiver locally generates a replica of the Gold codes for use in correlating with the incoming signal. To correctly match the timing of the codes for correlation, the receiver must also recover and track the clock rate for the codes generated in the transmitter. The clock is recovered by using a delay-lock-loop (DLL). The DLL has a duplicate of the Gold code generator that is in the transmitter. The DLL takes



7 BIT CODE LENGTH



DATA SIGNAL



RESULTANT SIGNAL

Figure 3.2 Data Modulation Through XNOR Gate

outputs from the FSR one gate early and one gate late, as compared to the prompt code. The early and late codes are then correlated with the incoming signal. Each of the resultant signals are then rectified and filtered to remove the data. By subtracting the resultant signals for the early and late correlation from each other a error voltage is obtained. The error voltage drives a voltage controlled oscillator (VCO) that is initially set at a frequency near to the expected frequency of the transmitter's clock. The output of the VCO is then feed back into the FSR, as the clock, to slew the generated code until it matches the rate of the received code. Once the receiver and transmitter are synchronized, the correlation of the incoming signal and the prompt code provides a signal that after low pass filtering (LPF), will yield the data. [Ref. 8]

B. ADVANTAGES OF CDMA

CDMA provides the advantages of being a system capable of handling several data stream on a single channel simultaneously without the restrictions on time or frequency separation associated with TDM and FDM. As a result of being able to use all of the channel all of the time by all of the data streams, channel efficiency can be regarded as being increased over that of a comparable TDM or FDM system. Additionally, problems common to FDM and TDM systems, such as crosstalk and intersymbol interference, are substantially

reduced by the increased processing gain associated with CDMA systems. Furthermore, the number of data streams accessing the channel simultaneously is typically five to ten per cent greater than the number on a similar FDM or TDM system while maintaining the bit error rate (BER) well within acceptable limits [Ref. 8].

C. LIMITATIONS OF CDMA

For all the advantageous aspects of CDMA there are some problems and limits encountered with its use. The major problem associated with CDMA is that when using very long length codes, it can take a long time for the receiver to synchronize with the clock of the transmitter. This results in the necessity of initializing the link between receiver and transmitter, to establish clock synchronization, before sending any data or accepting the prospect of losing data when a transmitter comes up on the channel. Also, when high data rates are required to be transmitted, the code rate must also increase. For any substantial number of data streams on the same channel simultaneously the code length must also be increased. The combination of these two factors, high data rate and large number of data streams, may result in clock rates up in the Gigahertz (GHz) ranges. This substantially increases the difficulty of actually building a CDMA system since it now must operate in the microwave region instead of radio frequency range.

IV. TRANSMITTER

A. DESIGN

Using the algorithms presented in references 5 and 6, a family of Gold codes was generated. A sequence of five delay states was selected. As seen in equation 3, this resulted in a code length of 31 bits. This arrangement also provides a family of 33 possible unique Gold codes. However, only two of the 33 codes were used for transmitting two data streams. The specific codes used were selected at random so that the ability to recover data, from two data streams, sent over the same fiber optic channel using CDMA could be demonstrated. The data rate and code clock rates, related by equation 2, are set at 1 KHz and 31 KHz respectively.

B. IMPLEMENTATION

The hardware used to construct the FSRs are 7486s (quad 2-input positive XOR gates) and 74164s (parallel-input/serial-output 8 bit shift registers) clocked at 31 KHz. WAVETEK model 143 function generators are used to provide the clock and data inputs at 31 KHz and 1 KHz respectively. Figure 4.1 shows the implementation of a 5 stage FSR using the above components. Figure 4.2 shows each of the resultant Gold codes generated by the FSRs. Each of the sequences is passed

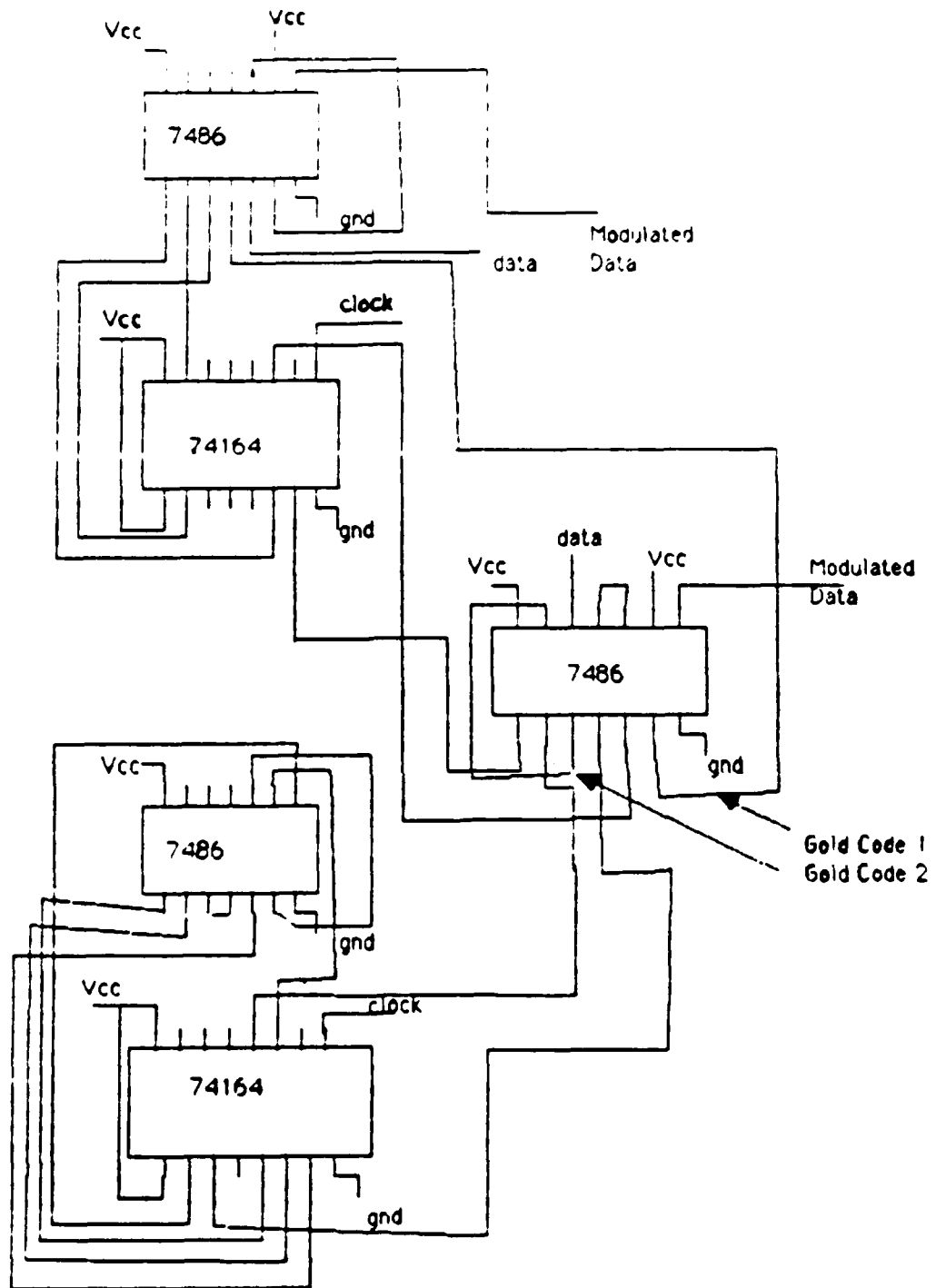


Figure 4.1 Gold Code Generator

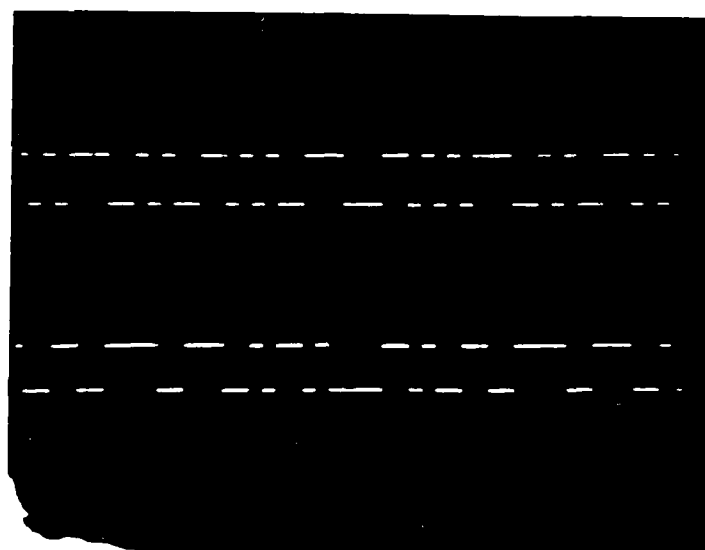


Figure 4.2 Generated Gold Codes

through 0.1 microfarad coupling capacitors to convert each of the unipolar sequences to bipolar form. The two sequences are then added together through two LM318 operational amplifiers configured as an inverting summing amplifier with unity gain and an inverter as shown in Figure 4.3. Figure 4.4 shows the resultant tri-level signal at the output of the summing amplifier.

C. PERFORMANCE

The ability to correlate each of the sequences is verified by taking the tri-level signal and multiplying it together with its separately generated and clocked identical twin Gold code. By slowing down one of the clocks, relative to the other code's clock, a strip chart recording of the crosscorrelation can be made as is shown in Figure 4.5. From Figure 4.5 the autocorrelation to crosscorrelation ratio was measured. The autocorrelation peak is the largest positive peak and the crosscorrelation peak is the next highest positive peak found. The measurements showed an autocorrelation to crosscorrelation ratio of 2.7 dB. This is well above the figure of 1.7 dB predicted by reference 5 for worst case situations. These results indicated that it is possible to recover data transmitted using this type of CDMA implementation.

In the final design, a much high clock rate was required to accommodate the 166.67 KHz Manchester encoded data rate.

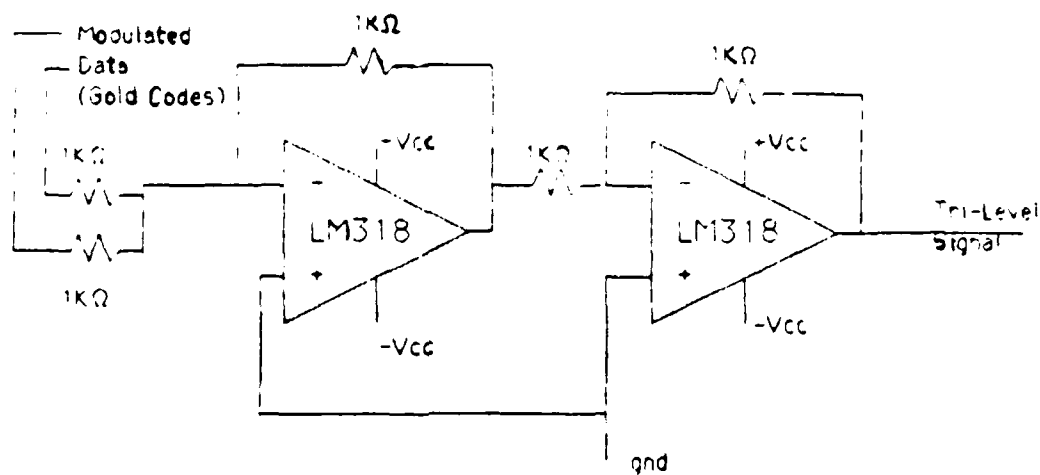


Figure 4.3 Operational Amplifier Summer

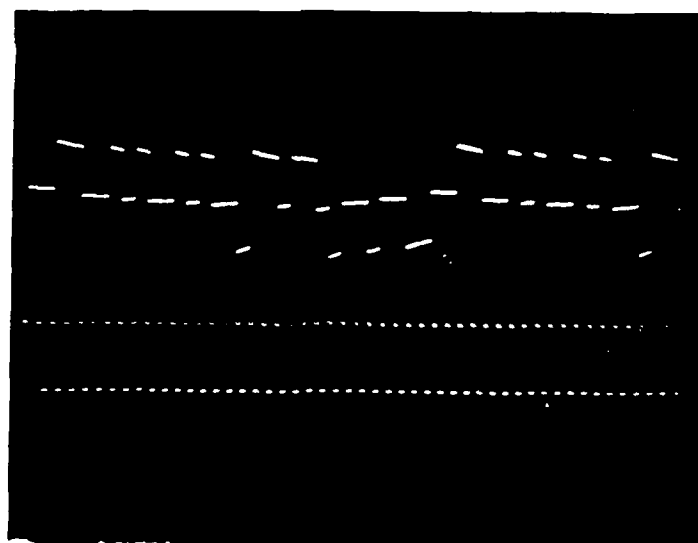


Figure 4.4 Summed Gold Codes

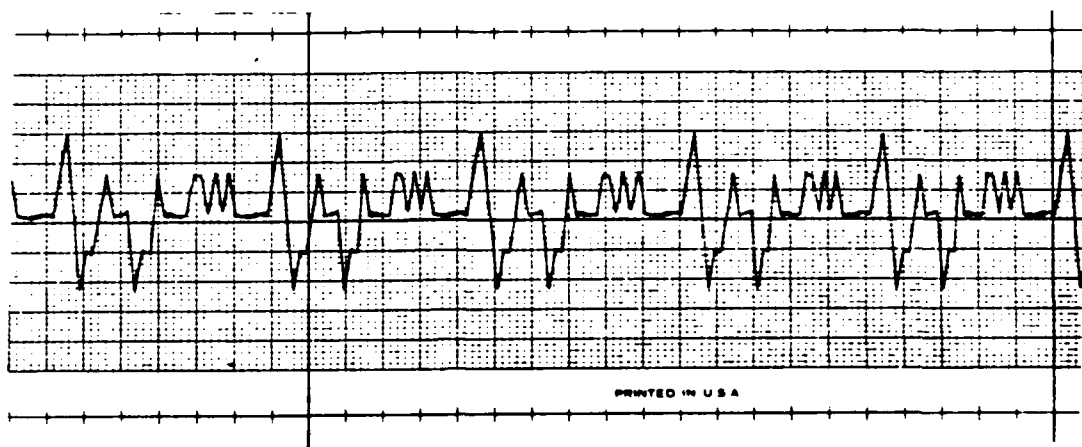


Figure 4.5 Correlation of Summed Gold Codes

The new code rate clock is 5.167 MHz. Devices for the construction of this higher speed circuit are CMOS 74F86s and 74F164s for the FSRs. Their configuration is exactly the same as in the lower speed circuit. The clock was supplied by a RACAL-DANA 9082P Synthesized Signal Generator driving a Hewlett Packard 8011A pulse generator. This arrangement increased the stability of the clock which is necessary since any frequency deviation in clock speed induces errors in the correlation process. The two channels were summed together through an EL2020CN high speed operational amplifier configured as a non-inverting amplifier with a gain of 0.160. An adjustable DC offset voltage is added to the summing amplifier to provide the positive bias required by the unipolar optical transmitter. This low value of gain is required since it is necessary to reduce the maximum voltage applied to the optical transmitter from its 10 volt original value to 2.33 volts. Additionally, the DC offset voltage allows the spread of voltage levels for the tri-level signal to be adjusted so that one level (the original 10 volt level) will be 2.3 volts, the next level (the original 5 volt level) will be 1.7 volts, and the lowest level (the original 0 volt level) will be below the 1.5 volt minimum voltage necessary to turn on the optical transmitter. Further details of the optical transmitter design are discussed in the next section. The high speed transmitter design is shown in Figure 4.6.

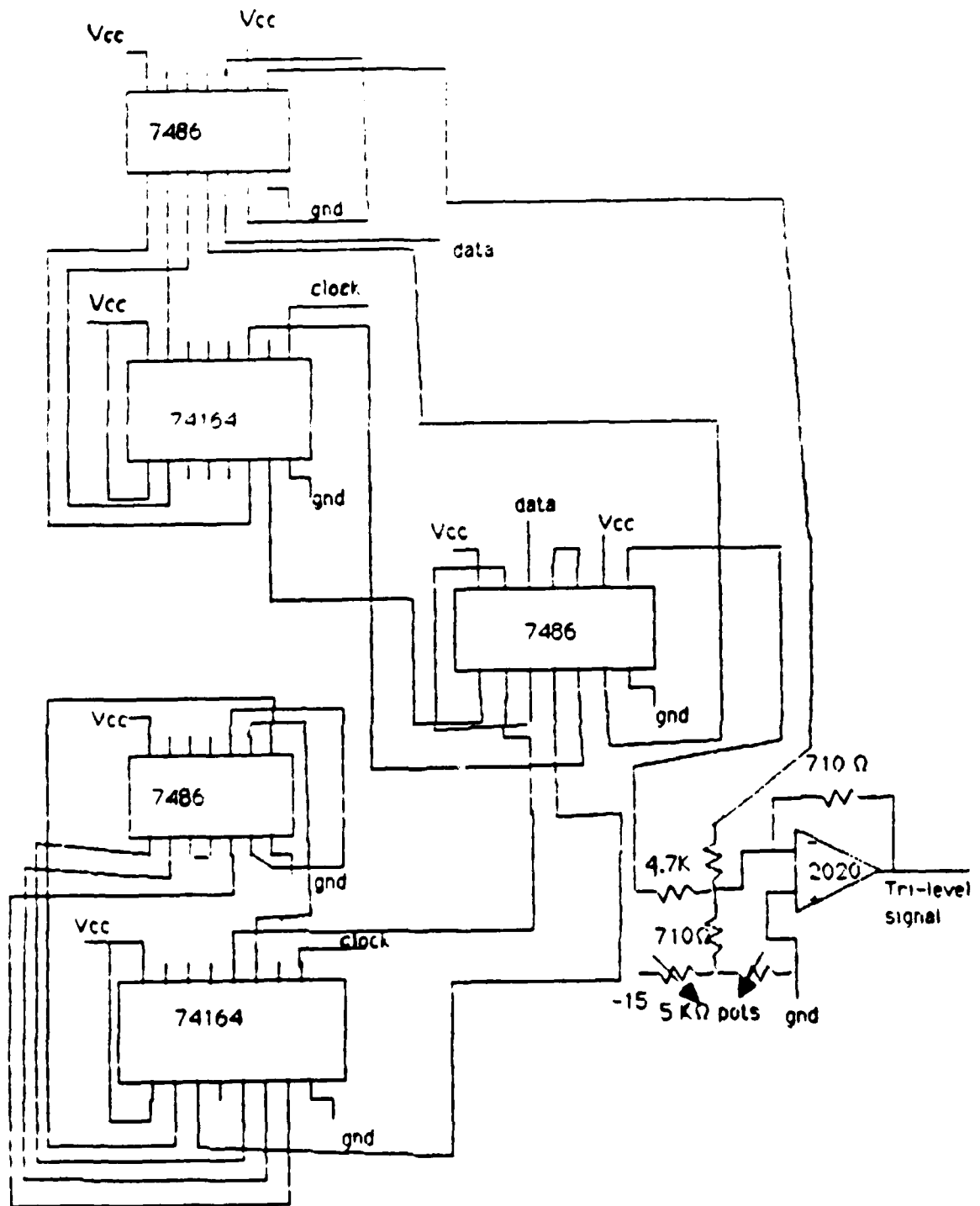


Figure 4.6 High Speed Transmitter Circuit

V. OPTICAL FIBER DATA LINK

A. DESIGN

The design process for the optical fiber data link is concerned with the selection of the proper optical transmitter, fiber, and optical receiver. The selection of these three components is entirely based upon the clock rate of the code, since clock rate sets the bandwidth required to be transmitted. For the initial test design, a clock at 31 KHz is used. A system with a 25 MHz bandwidth was constructed using Hewlett Packard's HBFR-0400 series components.

B. IMPLEMENTATION

The data link was constructed to meet the requirements of transmitting the upper two signals of the tri-level signal provided by the summing amplifier discussed in the previous section. Figure 5.1 shows the fiber optic data link. The HBFR-1402 transmitter is driven by a simple voltage divider which reduces the 10 volt maximum level signal to 2.3 volts. Pin 3 of the transmitter is provided with a 39 ohm shunt to ground to prevent overdriving the transmitter.

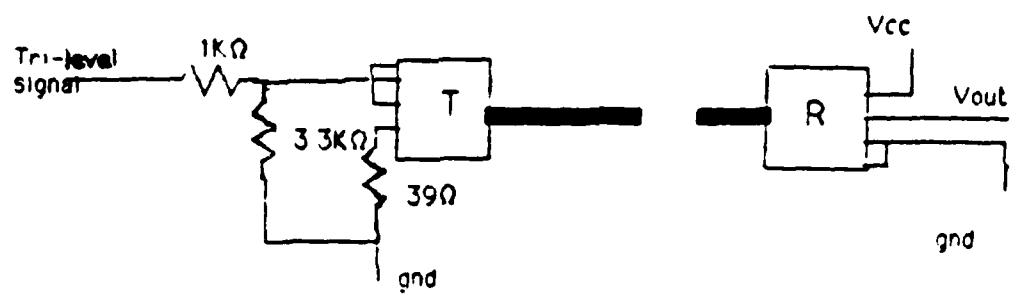


Figure 5.1 Fiber Optic Data Link (31 KHz)

The output voltage from the HBFR-2404 analog receiver is nominally stated as:

$$V_{out} = V_{odc} - (R_p \times P_r) \quad [7]$$

where V_{odc} is 0.7 volts when $P_r = 0$ microwatts (i.e., no light is received) and R_p is 7 millivolts/microwatt [Ref. 2]. Assuming that the maximum input power to the receiver is optimized to -12.6 dBm, which converts to 55 microwatts, then V_{out} is 0.6 volts. To recover the maximum potential signal, which is 10 volts, an amplifier with a gain of -16.6 is required. The inversion is necessary since the HBFR-2404 inverts the received signal. A LM318 operational amplifier was configured in the inverting mode to provide a gain of -16.6. Additionally, to pass only the frequencies of interest, a simple R-C network LPF, with a center frequency, f_c , equal to 31 KHz was used. Figure 5.2 shows the amplifier and low pass filter circuits.

C. PERFORMANCE

System performance for the 1 KHz data rate link is a measure of maximum link length. This measurement is assessed by performing an optical power budget calculation upon the link. Using Photodyne's fiber optic multimeter, model 22XLA, a measured optical power of -13.7 dBm is found present at the receiver end of the fiber link. The minimum optical power

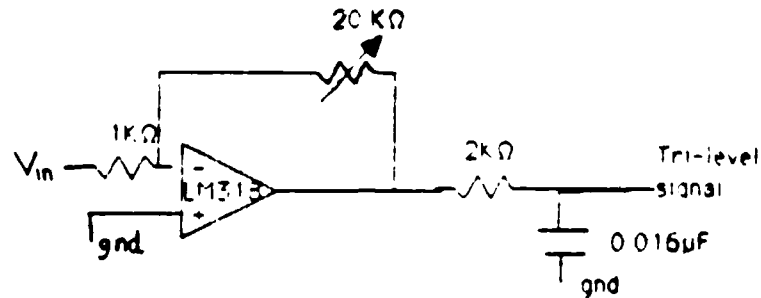


Figure 5.2 Amplifier and Low Pass Filter (31KHz)

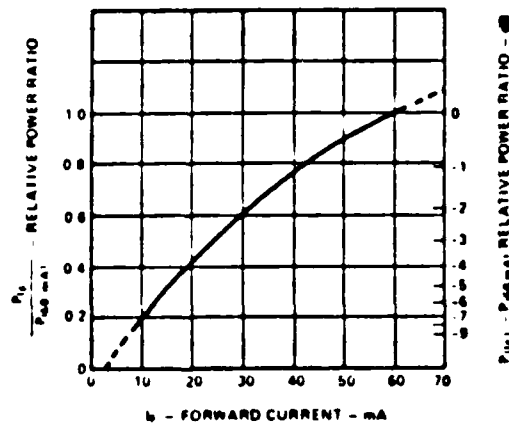


Figure 3. Normalized Transmitter Output vs. Forward Current

Figure 5.3 Forward Current versus Transmitter Power [Ref. 2]

necessary for the receiver to detect a signal is -25.4 dBm [Ref. 2], leaving a margin of 11.7 dB. This minimum value must be set by the middle level signal of the tri-level signal. Thus, the middle level signal sets the maximum cable length. Referring to Figure 5.3, a drive transmitter current of 30 mA has a relative power ratio of -2.2 dB referenced to a 60 mA signal. Assuming that the maximum power level obtained at the receiver end of the 1 meter cable was from a 60 mA signal (highest level signal) it is seen that the 30 mA signal should produce an optical power output of $-13.7 \text{ dBm} + -2.2 \text{ dB}$ or -15.9 dBm . From reference 2, it is assumed that cable attenuation is 6 db/km, therefore this link has a maximum cable length of 1.58 km. By reducing the difference between the middle level signal and the high level signal of the three levels, a greater length link can be achieved. However, an upper limit is placed on the optical transmitter's output power before it saturates, ultimately limiting the length of the link. Finally, the amount of noise present in the electrical signal driving the transmitter limits the difference between the upper two level signals before noise corruption makes the two levels indistinguishable. Therefore, some sort of decision process must be used to establish the minimum difference in the upper two level signals before the probability for an to occur error becomes too large.

In the final design phase a link capable of handling a clock speed of 5.167 MHz was required. Again Hewlett Packard's

HBFR-0400 series components provide an implementation that has the necessary bandwidth. The circuits for the higher speed data link are the same as the slower speed link except that operational amplifiers of higher speed were used. Figure 5.4 shows the circuit diagram for the data link.

The driver circuit for the transmitter is built around an Elantec EL2003CN high speed video driver. As in the previous design, only the upper two levels of the signal must be sent. Since the summing amplifier, discussed in the previous section, has already established the maximum voltage level of 2.3 volts, the video driver serves to increase the drive current to the optical transmitter. This is required since the EL2020CN operational amplifier used has a maximum output current of only 33 mA.

The receiver circuit for the high speed data link was also designed around the same basic circuits as in the slow speed data link. The difference is again due to the use of higher speed operational amplifiers. EL2020CN operational amplifiers are used to provide the gain at the output of the receiver. Each operational amplifier provides gains of -1.6, -2.0, and -5.0 for an over all gain of -16.0. Additionally, the first operational amplifier provides an active low pass filter with a center frequency, f_c , of 5.2 MHz. This low pass filter is a form of the Sallen-Key circuit and was designed in accordance with reference 9.

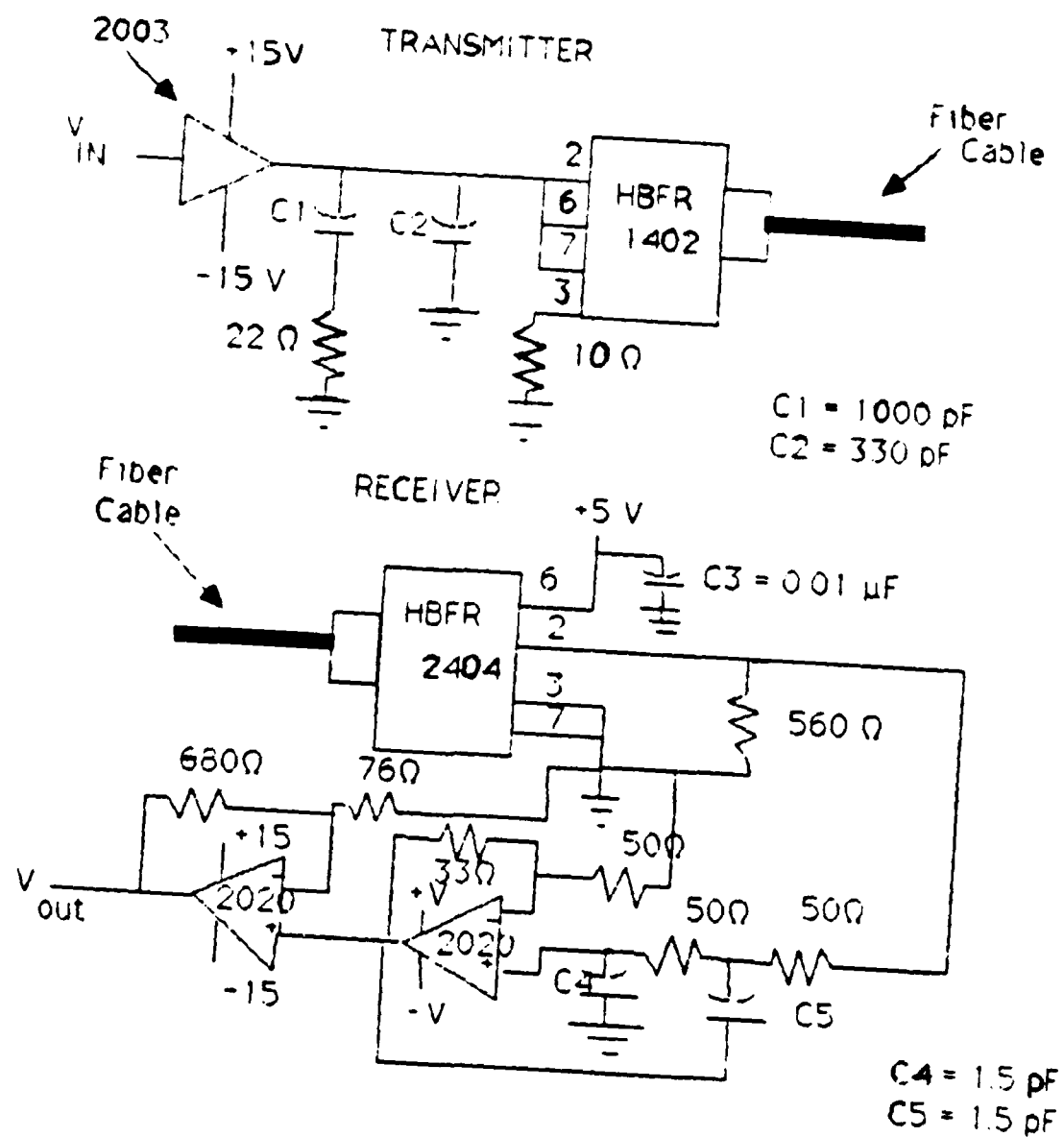


Figure 5.4 High Speed Data Link

VI. RECEIVER

A. DESIGN

The typical CDMA receiver is implemented by using a PLL circuit designed around a early-late gate correlation process to recover the clock speed. Once the proper clock speed is recovered, the appropriate Gold code is multiplied together with the incoming signal. The product of the multiplication process contains frequency components representing the data rate and its harmonics as well as harmonics of the code rate. When passed through a low pass filter which a cutoff frequency slightly above that of the data rate, the baseband data signal is recovered.

The PLL implementation of the early-late gate correlator for clock recovery represents a complex problem in itself. In the interest of pursuing the major goal of this thesis, the demonstration of CDMA over a fiber optic data link, an alternative method of achieving code rate synchronization between the transmitter and the receiver was selected. The alternative method of achieving code rate synchronization, thereby ensuring that autocorrelation will produce its peak value, is to provide the Gold codes, generated by a duplicate of FSR in the transmitter and manually adjust the frequency of the WAVETEK function generator. This will additionally allow

the autocorrelation peak and crosscorrelation peak to be measured when the clock frequency of the receiver's FSR is slightly off from the transmitter's FSR clock frequency. This provides a relatively simple and direct means of demonstrating the ability to correlate and recover data.

B. IMPLEMENTATION

In the initial design system, with a clock speed of 31 KHz, the correlation process was performed with an AD534 analog voltage multiplier. Data recovery was achieved through a simple R-C network low pass filter, with a corner frequency, f_c , of 1 KHz. Since there was no prior filtering performed on the transmitted signal, no delay of the Gold codes was required. Figure 6.1 shows the correlator and low pass filter circuits.

C. PERFORMANCE

In the initial design, with the 31 KHz clock, the maximum autocorrelation peak to crosscorrelation peak difference is predicted to be 1.7 dB under the worst circumstances [Ref. 5]. For a system that now is carrying data on the Gold codes, there should be no additional interference introduced into correlation process. Figure 6.2 shows a photograph of the correlation process performed on one of the two data streams. The autocorrelation peak measured 5.6 volts high, while the crosscorrelation peak measure 3.6 volts high. The

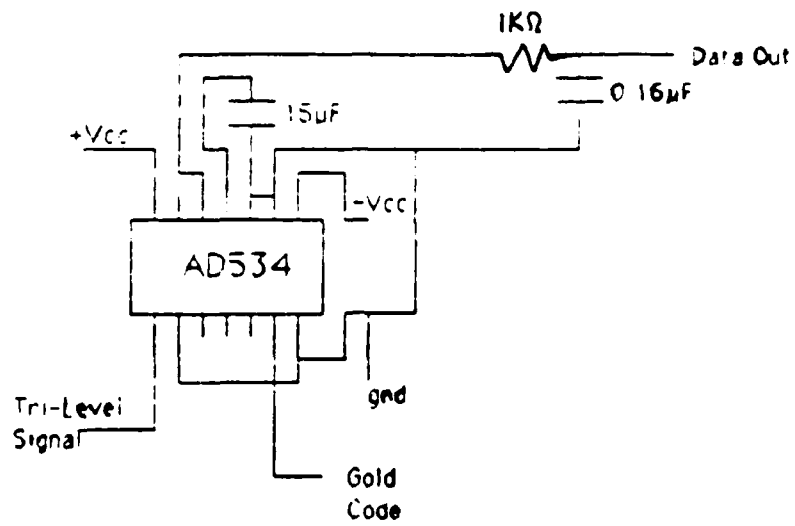


Figure 6.1 Correlator and Low Pass Filter (31 KHz)

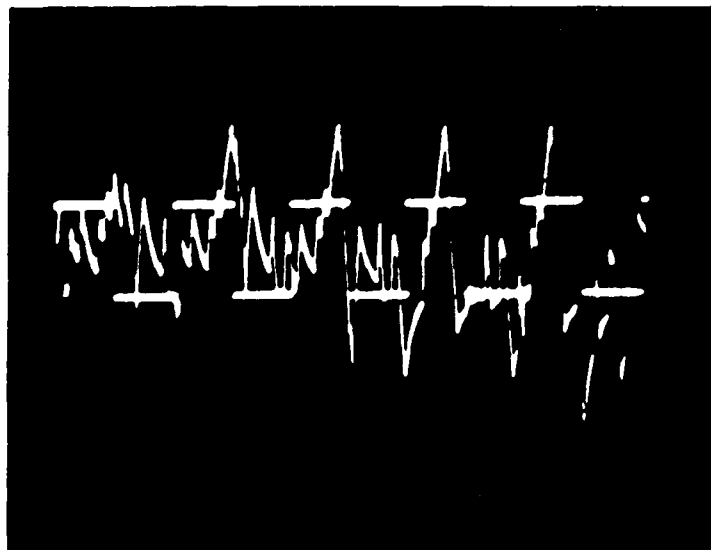


Figure 6.2 Correlation with Data Present

autocorrelation peak to crosscorrelation peak was 1.92 dB. This is still greater than predicted by reference 5, yet it is less than the value measured without the data present and before transmission over the data link. It is expected that as the number of data streams present on the channel increases, the measured autocorrelation to crosscorrelation peak ratio will approach the worst case situation of 1.7 dB.

In the final high speed design, the correlator is implemented with a XR-2208 operational multiplier. The output of the operational multiplier is passed through an active LPF, of the Sallen-Key form, designed for a corner frequency of 200 KHz, in accordance with procedures of reference 9. Figure 6.3 shows the multiplier and low pass filter circuits. Clock synchronization between the transmitter and receiver was not addressed, yet the early-late gate correlator PLL is envisioned as the method of choice. The lack of components and time prevented any further investigation from occurring on the high speed receiver.

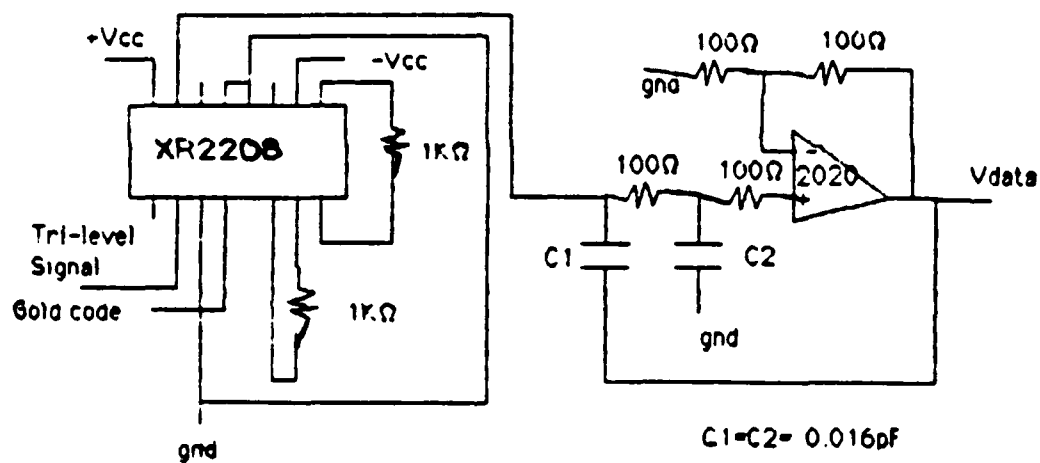


Figure 6.3 High Speed Correlator and Low Pass Filter

VII. SYSTEM PERFORMANCE

A. BIT ERROR RATE

To measure the bit error rate in the 31 KHz system, a Hewlett Packard 1645A Data Error Analyzer was used. The data input is removed and the data output from 1645A is connected to the XNOR for modulation with the Gold code. Data out of the LPF after the AVM is returned to the 1645A for comparison. The 1645A is clocked at 2400 baud, which is 1200 bits per second. Since this is higher than the original data rate, the Gold code generator's clock was boosted to 36.2 KHz. Under these circumstances the bit error rate was found to be 1.2×10^{-9} . This measurement is slightly worse than the theoretical value, from reference 2, of less than 1×10^{-9} for the fiber link; yet, the inclusion of a slightly unstable clock for the Gold code generator could cause this variation.

B. BANDWIDTH VERSUS DATA RATE

The constraining component of the CDMA fiber optic link is the available bandwidth of the fiber optic link. Since bandwidth directly relates to code rate and the code rate is driven by the data rate and the number of bits in the code, it is reasonable to conclude that the bandwidth of the fiber optic link sets the maximum data rate.

For the sensors in this system, frequency response is required to be from 0 to 20 KHz. When sampling at ten times the highest frequency present, a sampling rate of 200 Kbps results. If each sample is converted into a 12 bit Manchester word, a bit rate of 2.4 Mbps results; but since each Manchester bit is actually a two state signal, the bit rate is twice or 4.8 Mbps. When code length is brought into the picture as per equation 1, a plot of data rate versus channel bandwidth as a function of code length can be generated, as shown in Figure 7.1.

The horizontal dashed line, in Figure 7.1, represents a channel bandwidth of 25 MHz, which is the bandwidth of the HBFR-0400 components used. Using the 25 MHz as the limit on bandwidth, the frequency response of the sensors is limited to 6.9 KHz, 3.4 KHz, and 820 Hz for Gold code lengths of 15, 31, and 127 bits respectively. Therefore, this particular CDMA implementation over a fiber optic data link does not meet the initial requirements of frequency response. The alternatives available are to decrease the sampling rate, use a shorter Manchester code or eliminate the use of Manchester code altogether, and/or use optical components with a greater bandwidth. If the last option is eliminated, as was the case due to a lack of affordable components, and you are restricted to using the 25 MHz bandwidth components, the combination of reducing the sampling rate and reducing and/or eliminating the Manchester encoding will meet the frequency response

requirements of the system so long as the effects of sampling rate and analog to digital conversion do not represent greater than a 40 fold increase when using a code length of 31 bits. This option does not exist when using Gold codes of increased length.

BANDWIDTH VERSES DATA RATE

SAMPLING TIMES 10, 12 BIT WORD

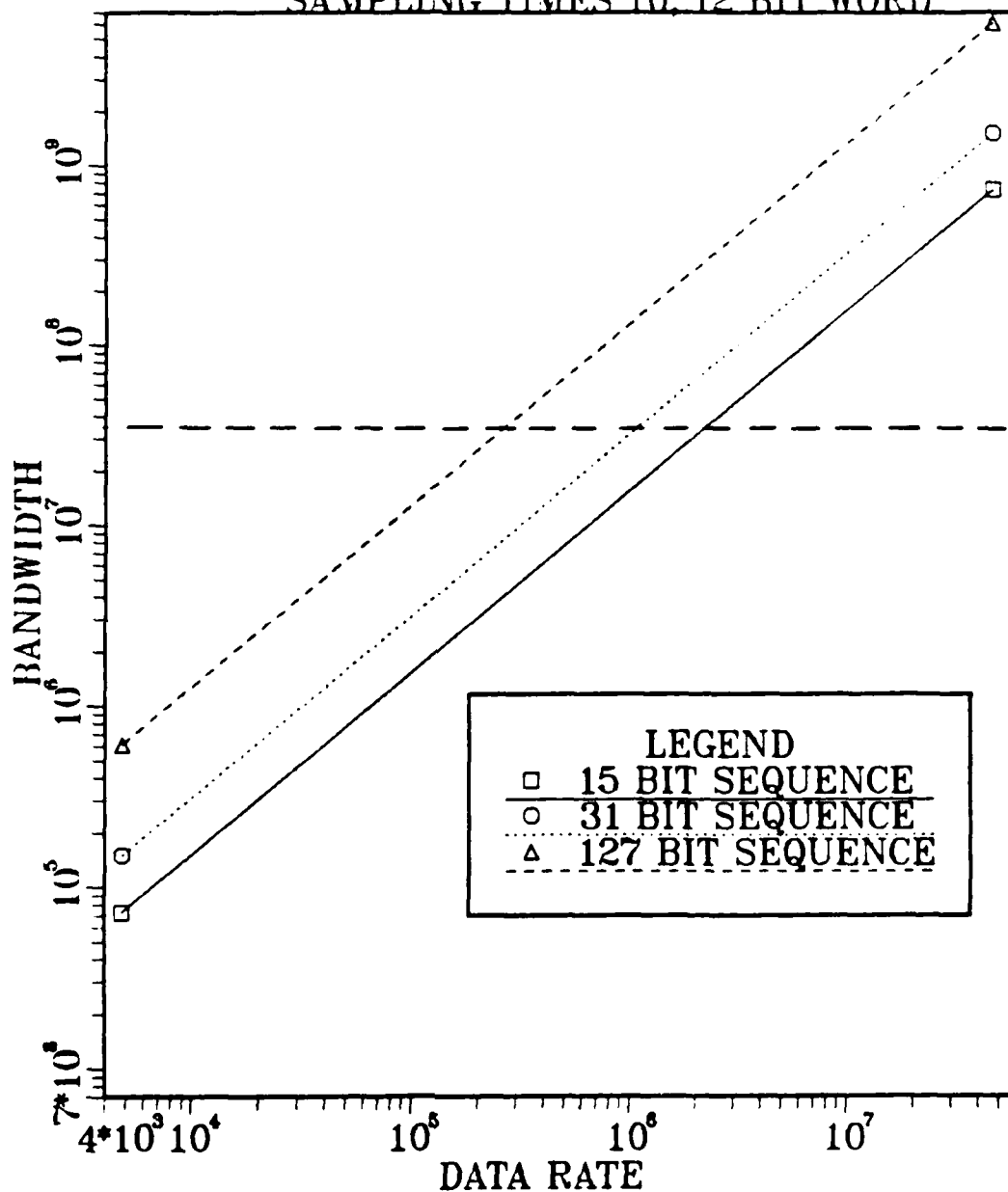


Figure 7.1 Bandwidth versus Data Rate

VIII. CONCLUSIONS

The aforementioned systems of FDM, TDM, and CDMA all provide the capability to carry multiple data streams on one channel. None are without limits; however, CDMA appears to have less significant theoretical limitations. A CDMA scheme for employment as the channel from multiple sensors seems to be the least limited of all systems. The speed at which it is necessary to operate a CDMA system of any significant data handling capacity (data rate and number of data streams), introduces considerable physical complexity and cost into the problem.

The initial design of a 1 KHz data rate system demonstrated the ability to send data over an optical data link in a in a three level state. However, as the number of carriers on the channel is increased, the number of levels present also increases at a rate of $2^n - 1$. Thus differences between the discrete levels that the transmitter and receiver must be able to differentiate decreases and noise can become a significant problem. Very sensitive receivers, typically an avalanche photo diode (APD) could solve this problem, yet it would be restricted in the dynamic range of signals it could respond to. Thus the problem is not easily answered by the selection of one type of optical receiver over another, but

involves the considerations of number of levels necessary to be transmitted over the optical data link and the amount of noise present in the electrical portion of the system used to generate the Gold codes and modulate the data. Also, the optical transmitter must have a very high slew rate so that the small incremental changes in levels can be obtained without distortion.

The real potential of CDMA remains to be exploited. Through optical signal processing, the major problems of code rate timing and electronic noise can be eliminated. Figure 8.1 illustrates a potential optical CDMA system. In this system the codes are generated in the same manner as in the systems designed in this thesis. The encoded data drives a laser which converts the electrical signal into optical pulses. The data streams from several fibers are combined onto a single fiber through a star coupler. After transmission on the single fiber, the fiber is split into a number of fibers which all have different lengths. The different lengths of fiber delay the pulses present on the fiber much the same as in a surface acoustic wave device. The result of the delay is then recombined onto a single fiber. At this point an impulse is present; this is feed into an APD for conversion to an electrical impulse. If the impulse is of sufficient magnitude, the threshold detector is triggered to produce a pulse that corresponds to a data bit of "1".[Ref. 10] Because of the high speed of operation that can be achieved

with this type of system, future efforts should be in the area of optical CDMA implementation using optical signal processing.

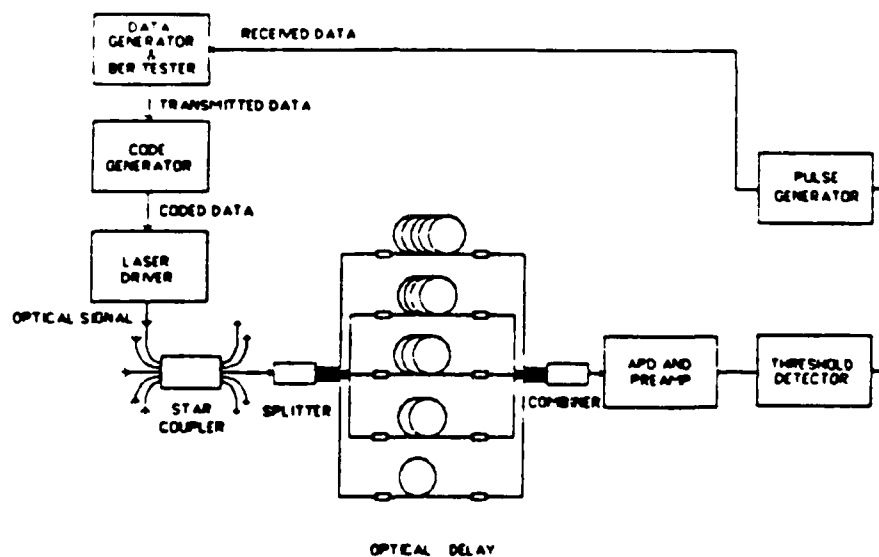


Figure 8.1 Optical CDMA System [Ref. 10]

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